Predicting Upwelling Radiance on the West Florida Shelf

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LONG-TERM GOALS

The prediction of inherent optical properties (IOPs) and water-leaving radiance (L_w) in coastal waters over a 5 to 10 day time horizon will require a numerical simulation that accurately forecasts the physical, ecological, and optical environment. Critical to the ecological and optical forecast is the ability to directly compare the water-leaving radiance field to those being collected by aircraft and satellite platforms. Our goal is to develop the ecological and optical models and computer codes to initialize, validate, and predict the IOPs and L_w over an operational time horizon.

OBJECTIVES

1) Couple EcoSim 2.0 to a robust radiative transfer model to yield water-leaving radiance for a given IOP distribution

2) Initialize and validate spectral water-leaving radiance with remote sensing data.

3) Couple EcoSim 2.0 to the WFS version of the Regional Ocean Modeling System (ROMS)

APPROACH

The pace of development of prognostic ecological/optical data and modeling systems has greatly accelerated in recent years such that we can now reasonably discuss the likelihood of predicting red tides, and concomitant impacts on water clarity on the West Florida Shelf (WFS). Accurate prediction of water clarity and color suggests a fundamental knowledge of marine ecological systems, and the validation of such data and modeling systems would provide characterization of the littoral environment over operational time horizons. Water clarity and color are directly dependent on the IOPs of the water column and the modeling component of these prognostic systems requires a fundamental set of equations that describe the interactions between the production and destruction of the IOPs. As the IOPs of absorption, scattering, and the scattering phase function can be described by a summation of the individual components, the cycle of color can be described by equations representing the individual active color constituents, i.e., phytoplankton, organic detritus, Colored Dissolved Organic Matter (CDOM), sediments, bathymetry, and bottom classification. The description of the cycling of each component allows for feedback effects between the in-water light field and the production and destruction of color.

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14. ABSTRACT
The prediction of inherent optical properties (IOPs) and water-leaving radiance (Lw) in coastal waters over a 5 to 10 day time horizon will require a numerical simulation that accurately forecasts the physical, ecological, and optical environment. Critical to the ecological and optical forecast is the ability to directly compare the water-leaving radiance field to those being collected by aircraft and satellite platforms. Our goal is to develop the ecological and optical models and computer codes to initialize, validate, and predict the IOPs and Lw over an operational time horizon.

15. SUBJECT TERMS

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The marine optical environment may change at the same time scale of weather change, so any operational prognostic optical system would need to be embedded into a larger system of data collection and numerical modeling. Such a system would use moorings, ships, Autonomous Underwater Vehicles (AUVs), satellites, and physical/ecological/optical numerical models to provide integrated data streams to a wide community of users. The systems would need to be able to assimilate data as it became available, and provide forecasts over a wide range of time and space scales. The West Florida Shelf (WFS) is an ideal location to help develop these nowcast/forecast systems, in part due to a large number of other research programs focused on the WFS, including other ONR funded technology programs, NOAA/EPA ECOlogy of Harmful Algal Blooms (ECOHAB) program, and the State of Florida Coastal Ocean Monitoring and Prediction System (COMPS) program. The ECOHAB and COMPS programs are focused on time scales ranging from months to years and spatial scales ranging from kilometers to 1000s of kilometers. Therefore, this site provides a natural location to develop broad scale time and space models of the inherent optical properties.

The WFS is unique in other ways that make it ideal for the development of forecasting systems. In particular, the variance in color and clarity of the near-shore waters is extreme, ranging from oligotrophic Case 1-type waters to highly attenuating Case 2 waters (Bissett et al., 1997; Carder and Steward, 1985; Carder et al., 1989). The low-nutrient and low-colored waters of the WFS are derived from the oligotrophic waters of the central Gulf of Mexico and the waters of the Caribbean Sea via the Loop Current. These waters have typical open ocean color signals. In the deeper waters off the shelf, the variations in surface color are driven by seasonal nutrients and CDOM introductions via deep mixing, as well as eddy fluxes, much like the classic understanding of Case 1 ocean color. As one moves across the shelf break onto the outer shelf, complications to the classic blue ocean signal arise from both Loop Current intrusions that bring higher nutrient waters (and CDOM) into the euphotic zone and river CDOM fluxes from the Mississippi, Mobile, and Apalachicola Rivers. In the inner shelf, the color signal becomes even more complicated as the introduction of waters from Suwannee, Hillsborough, Peace, and Caloosahatchee Rivers mix with the above water masses, as well as with those waters created locally from high energy mixing (waves, long-shore currents, etc.) and heat flux imbalances.

The ecological/optical conditions on the WFS are as complicated as any coastal region, yielding situations where the chlorophyll a biomass may range from 0.01 to >20 μg liter^{-1} at the same location during different time periods. When oligotrophic waters dominant the shelf, bottom features are clearly evident in high-resolution hyperspectral data to a depth of 30 meters. At other times, river and estuary waters dominate, and the bottom is undistinguishable in waters <2 meters deep. In between these two conditions, the color signal is mainly a function of the ecological interactions between phytoplankton growth and loss and CDOM creation and destruction. Within the inner shelf, the color signal is further modified by the bottom classification and sediment re-suspension. Our goal on the WFS is to derive and validate a set of fundamental ecological/optical/physical equations that addresses, and eventually predicts, the complexity of the IOPs and the resultant water-leaving radiance. This site is an ideal location for the regional time and space scales being studied.

WORK COMPLETED

The work in FY2003 focused on publication of ecological and optical results from the 2-D simulation of the WFS. With the integration of the shoreward boundary condition for nutrients and color, the simulation showed robust comparisons to the satellite imagery for 1998 (see also Progress Report

Bissett, N000140010411, for a discussion on the CDOM impacts of the shoreward boundary condition). In addition, the use of HPLC data, collected during November 1998, allowed us to validate the ecological predictions of phytoplankton competition with respect to differential light and nutrient utilization. These results have been submitted for publication in a volume of UNESCO Monographs on Oceanographic Methodology-Manual on Harmful Marine Microalgae (Bissett et al., 2003b).

In conjunction with Dr. C. Mobley (N0001497C0019 and N00014D01610002), we have integrated a very fast, radiometrically robust, radiative transfer code (Ecolight 4.1) with the ES2 IOP output data stream. This integrated EcoSim/Ecolight formulation allows us to directly simulate remote sensing reflectance, $R_{rs}(\lambda)$, which may be compared directly to satellite and aircraft remote sensing data. This allowed us to explore errors in the simulated IOP fields, as well as focus on the possible errors in the satellite derived IOP fields in near-shore waters. In addition, the downwelling irradiance model used in EcoSim to drive the time-dependent ecological change in IOPs is an approximation, which was derived in an earlier version of EcoSim (Bissett et al., 1999a; Bissett et al., 1999b). The results of these approximations were tested against the more robust radiative transfer model, Ecolight, and the results of the error analysis between these models are being prepared to be submitted for publication.

Lastly, our plan to generate a 3-dimensional prediction of upwelling radiance on the West Florida Shelf was based on a circulation model developed by the University of South Florida. However, this POM based code is not sufficiently robust to be used in this manner. We have decided instead to focus on the ROMS/TOMS code development (see Progress Report Schofield, N000149910196, and Bissett, N000149910198). In addition to being developed under an open source agreement between multiple institutions, it is being designed to have nested grids for multiple spatial scale resolutions, as well as being transportable to many different massively parallel computer platforms. We believe that this is the best approach to generate a code set that is more likely to be transitioned to the naval, geophysical, and biogeochemical research community.

RESULTS

The ecological results demonstrate the importance of the terrestrial influences on the IOP distributions. In particular, the increase in nutrient concentrations driven by terrestrial fluxes from the Charlotte Harbor Estuary show orders of magnitude increase in nitrogen, silica, and phosphorus in both organic and inorganic forms (Bissett et al., 2003b). These nutrient fluxes led to phytoplankton accumulations that were both remotely sensed by SeaWiFS and simulated in this study. Figure 1 shows the satellite estimated and simulated surface total chlorophyll following Hurricane Georges and Tropical Storm Mitch. The simulated near-shore values without the pulse of estuarine water from Charlotte Harbor are clearly outside of 1 standard deviation (s.d.) of the satellite estimated chlorophyll a concentration. The very high simulated values near-shore on November 8th appeared to result from the inability of the 2-D physical simulation to adequately resolve the 3-D baroclinic flows around the southern end of the simulation range.

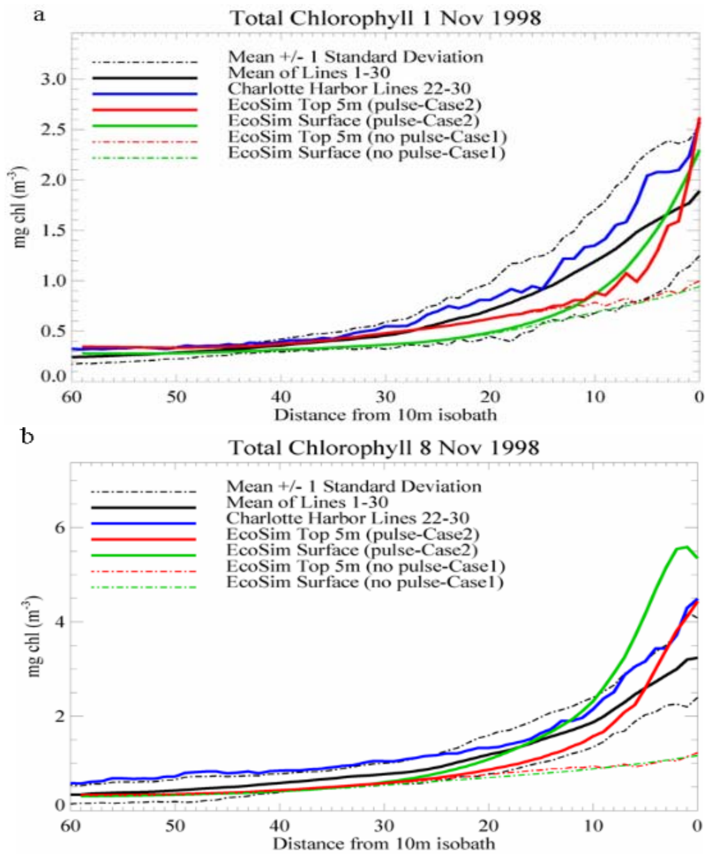

Figure 1: Simulated versus SeaWiFS Total Chlorophyll. (a) November 1, 1998, and (b) November 8, 1998. The simulated chlorophyll a values are within 1 standard deviation (s.d.) of the average satellite estimates across the shelf in the simulation runs which include a shoreward boundary condition (solid red and green lines). Without the shoreward boundary conditions, the nearshore simulated values drop below 1 s.d. of the satellite estimates. The higher values nearshore on November 8th overestimate the mean conditions, but are similar to the Charlotte Harbor estimates.

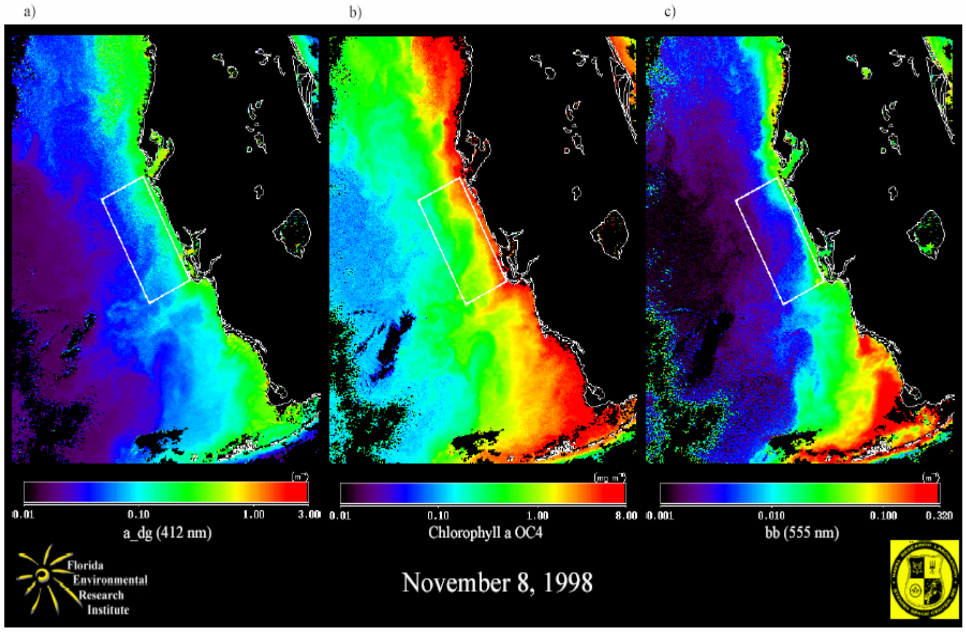

Figure 2: The West Florida Shelf, November 8, 1998. SeaWiFS estimated (a) absorption at 412m, $a_{dg}(412)$; (b) chlorophyll a (OC4 algorithm), and (c) backscattering at 555 nm, $b_b(555)$. The model domain is shown as the white box on each of the images. The SeaWiFS line plots on Figure 1 are derived by dividing the domain into 30 equally spaced lines and averaging them to create a statistically significant data set to compare against the 2-D simulation results. (a), (b) and (c) show the influence from local terrestrial freshwater sources of nutrients on the total color and chlorophyll signal in the model domain. Evident in the color and chlorophyll signals are the high concentration just south of the model domain and Charlotte Harbor, which was not adequately resolved by the 2-D physical circulation model. This is the source of some of the errors in Figure 1.

While the estimates of total chlorophyll and the distributions of chlorophyll amongst phytoplankton functional groups are reasonable in light model deficiencies (Bissett et al., 2003b), the simulated backscattering errors appear to be more systematically lower than the satellite estimates (Figure 3). These errors appear to result from 1) an inaccurate description of phytoplankton backscattering, 2) exclusion of sediments in the simulated IOPs, and 3) possible inaccuracies in the estimate of backscattering from the satellite signal. The first two sources of error are clearly problems that need to be addressed. The backscattering in EcoSim is currently a function of the total chlorophyll a concentration, developed for Case 1, open ocean conditions (Morel and Maritorena, 2001). While this formulation appears to be reasonable in the offshore region, it becomes more problematic near-shore. Figure 3b contains the satellite and simulation results following TS Mitch, and the near-shore backscatter is tremendously higher than Figure 3a (note the scale shift). The passage of a tropical storm would probably resuspend a fair amount of bottom sediments in this shallow water region, and it is highly likely that the exclusion of this IOP component is the reason for part of the error.

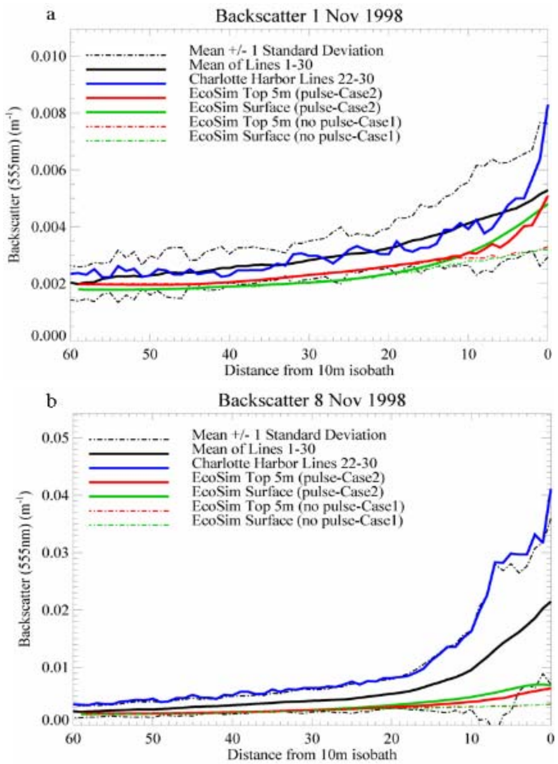

Figure 3: Simulated versus SeaWiFS Backscattering at 555 nm. (a) November 1, 1998, and (b) November 8, 1998. The simulate values are within 1 standard deviation (s.d.) of the average satellite estimates across the shelf in the simulation runs which include a shoreward boundary condition (solid red and green lines). Without the shoreward boundary conditions, the near-shore simulated values drop below 1 s.d. of the satellite estimates. The simulated values are systematically lower than the satellite estimates, possibly the results of 1) poor model formulation, 2) exclusion of sediment IOPs, 3) errors in the satellite formulation.

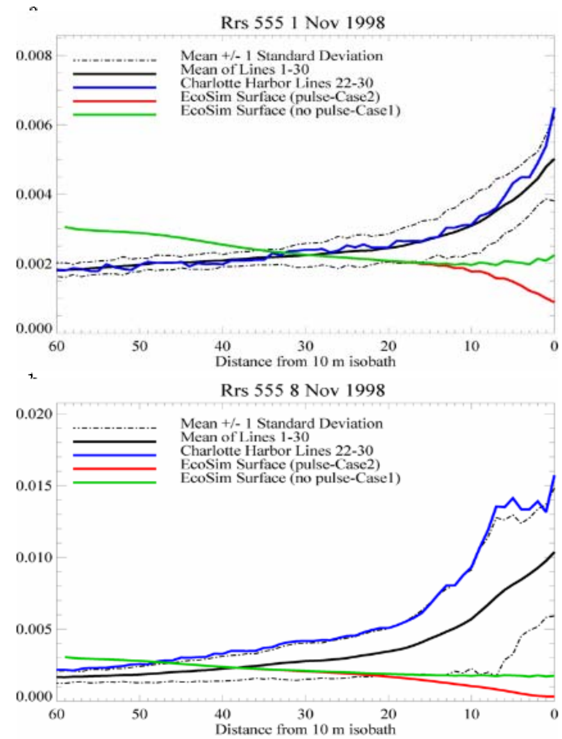

Figure 4: Simulated versus SeaWiFS Remote Sensing Reflectance at 555 nm. (a) November 1, 1998, and (b) November 8, 1998. These errors require additional study to understand. There is a clear scale shift following TS Mitch. In addition, the pattern of errors is not similar to the IOP errors for Figures 1 and 3. The resolution of these errors will require re-evaluating the NRLSSC Rrs calculations as well as the EcoSim/Ecolight coupling.

However, there was also a dramatic shift across the entire region in the satellite $R_{rs}(555)$ estimates (Figure 4) from November 1st to November 8th (again note the scale shift). It is unclear why there would be such a dramatic change, and this shift is currently under study. In addition, the errors between the satellite R_{rs} and the simulated R_{rs} across all wavelengths are much greater than the IOP products themselves. This too needs to be resolved. The satellite R_{rs} products are taken from the APS processing of the SeaWiFS data (R. Arnone, NRLSSC) and are derived differently than NASA's SeaWiFS processing in coastal waters to remove bottom and atmospheric contamination effects. This comparison of predicted versus satellite and aircraft R_{rs} will be one of the focuses in FY 2004. These ecological and optical results are more fully described in submitted publications (Bissett et al., 2003a; Bissett et al., 2003b).

Lastly, initial comparisons of the EcoSim downwelling approximations versus the more robust Ecolight downwelling calculations, using the same simulated IOP distributions, has yielded some interesting results (Figure 5). The errors between these two calculations of the propagation of downwelling irradiance appear most evident at lower light levels, and at high b/c values (data not shown). The EcoSim and Ecolight AOP solutions will also be further explored in FY 2004.

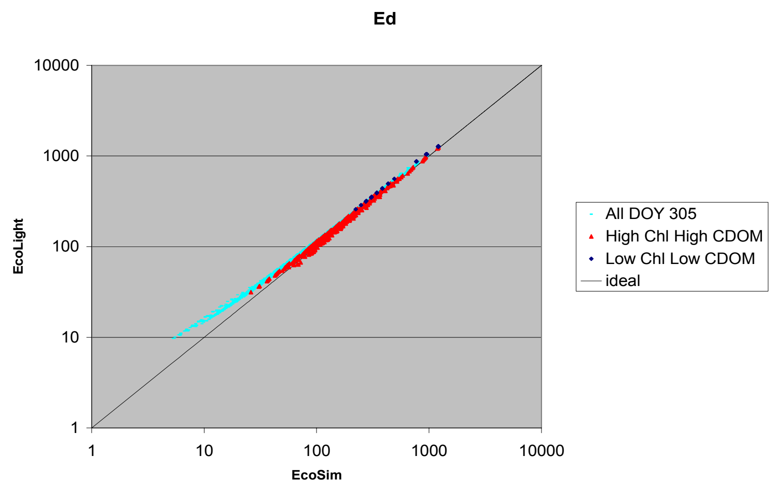

Figure 5: Ecolight versus EcoSim Downwelling Irradiance Comparison (data in μmol quanta m^{-2} s^{-1}). These were calculated over all depths and all horizontal grid point in the EcoSim 2-D model domain. The data shows very good agreement (nearly 1:1) except at light levels below ~80 μmol quanta m^{-2} s^{-1}.

IMPACT/APPLICATIONS

Forecasting IOPs over operational time horizons of 5 to 10 days will require the ability to directly compare predictions of water-leaving radiance to the data most likely to be used for initialization and validation of the predictions, i.e., aircraft and satellite hyperspectral remote sensing data. This effort will yield a simulation ready to begin direct data assimilation of the water column optical properties to predict absorption and scattering over short-term time horizons.

TRANSITIONS

The EcoSim 2.0 and Ecolight 4.1 are being developed as open source code and part of the ROMS/TOMS code set funded by ONR.

RELATED PROJECTS

We are collaborating with Dr. C. Mobley of Sequoia Scientific, Inc for the coupling of EcoSim with Hydrolight, and Drs. R. Arnone, NRL, and K. Carder, USF, for satellite data analysis.

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HONORS/AWARDS/PRIZES

2003 Small Business of the Year, Semi-Finalist, Florida Environmental Research Institute, W. Paul Bissett, Ph.D., Executive Director, Greater Tampa Chamber of Commerce.